D-A248 696

ASL-TR-0308

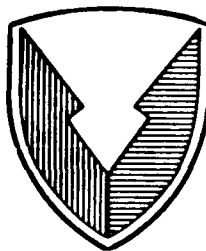# SENSITIVITY OF $C_n^2$ TO RANDOM VARIATIONS

# OF WINDSPEED, SENSIBLE HEAT FLUX, AND LATENT HEAT FLUX

March 1992

DTIC
SELECTE
APR 17 1992
S B D

Henry Rachele
Arnold Tunick

92-09591

**US ARMY
LABORATORY COMMAND**

92  4  16  009

NOTICES

Disclaimers

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

The citation of trade names and names of manufacturers in this report is not to be construed as official Government indorsement or approval of commercial products or services referenced herein.

Destruction Notice

When this document is no longer needed, destroy it by any method that will prevent disclosure of its contents or reconstruction of the document.

# REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503

| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE March 1992 | 3. REPORT TYPE AND DATES COVERED Final |
|---|---|---|

**4. TITLE AND SUBTITLE**
Sensitivity of $C_n^2$ to Random Variations of Windspeed, Sensible Heat Flux, and Latent Heat Flux

**5. FUNDING NUMBERS**

**6. AUTHOR(S)**
Henry Rachele and Arnold Tunick

TA: B53A-B611102.53A.40.11

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
U.S. Army Atmospheric Sciences Laboratory
White Sands Missile Range, NM 88002-5501

**8. PERFORMING ORGANIZATION REPORT NUMBER**
ASL-TR-0308

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
U.S. Army Laboratory Command
Adelphi, MD 20783-1145

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT (Maximum 200 words)**

The optical turbulence structure parameter, $C_n^2$, is a primary parameter in expressions used to characterize electromagnetic energy and image propagation through the atmosphere. Examples of these expressions include the receiver coherence diameter and the atmospheric modulation transfer function. In this analysis the authors write $C_n^2$ in terms of windspeed (V), sensible heat flux (H), and latent heat flux (L'E) assuming that their values are measured or modeled. Then the authors consider the effect on 2 $C_n^2$ if estimates of H. L'E, and V are assumed to be in error or vary (that is, due to sensor error and/or natural atmospheric variations). Micrometeorological data from Davis, California, are used to comprise two case studies. The results presented include bar charts of the modeled distributions of H; L'E; the surface friction velocity, $U^*$; the temperature and specific humidity scaling parameters, $T^*$ and $q^*$; the Obukhov scaling length, L; the reference level (1 m) windspeed, $V_r$; and finally $C_n^2$ for each case.

**14. SUBJECT TERMS**
optical turbulence structure parameter, sensible heat flux, latent heat flux, windspeed, similarity scaling parameters, micrometeorology

**15. NUMBER OF PAGES**
29

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | SAR |

# CONTENTS

3

# LIST OF ILLUSTRATIONS

## Table

## Figures

# 1. INTRODUCTION

The optical turbulence structure parameter $C_n^2$ is a primary parameter in expressions used to characterize electromagnetic energy and image propagation through the atmosphere. Examples of these expressions include the receiver coherence diameter, the atmospheric modulation transfer function, the isoplanation effective path length, and the scintillation average length (Miller and Ricklin, 1990).

A basic form of the equation often used for computing $C_n^2$ is given by Tatarski (1961) as

$$C_n^2 = b\left(\frac{K_h}{\epsilon^{1/3}}\right)\left(\frac{dn}{dz}\right)^2 \quad , \tag{1}$$

where

$b$ = a constant = 3.2 (obtained from Wyngaard (1973), Hill (1989), and Andreas (1988)),

$z$ = height above ground,

$K_h = u^{\bullet}\dfrac{kz}{\phi_H}$ = turbulent exchange coefficient for heat,

$\phi_H$ = dimensionless lapse rate = $\left(1 - 15\dfrac{z}{L}\right)^{-1/2}$, $L < 0$ (Hansen, 1980),

$k$ = von Karman's constant,

$\epsilon$ = energy dissipation rate = $\left(\phi_m - \dfrac{z}{L}\right)\dfrac{u^{\bullet 3}}{kz}$ (Panofsky, 1968),

$\phi_m = \left(1 - 15\dfrac{z}{L}\right)^{-1/4}$, $L < 0$ (Hansen, 1980),

$n$ = real index of refraction,

$L$ = Obukhov length,

$\dfrac{dn}{dz}$ = height derivative of n,

$u^{\bullet}$ = friction velocity.

In addition, $\dfrac{dn}{dz}$ is a function of the height derivatives of potential temperature and specific humidity, that is, $\dfrac{d\theta}{dz}$ and $\dfrac{dq}{dz}$. As such, a critical question would be how can we best approximate these derivatives. In our approaches, we assume that the environment is in a steady, horizontally homogenous state so that

$\frac{d\theta}{dz} = \frac{\partial\theta}{\partial z}$, and $\frac{dq}{dz} = \frac{\partial q}{\partial z}$. Furthermore, we assume that the derivatives are expressible in similarity form. For instance, for unstable conditions, the derivatives of potential temperature $\theta$, specific humidity q, and windspeed v are written as

$$\frac{\partial\theta}{\partial z} = \frac{\theta^{\bullet}}{kz}\left(1 - 15\frac{z}{L}\right)^{-1/2} \ , \tag{2}$$

$$\frac{\partial q}{\partial z} = \frac{q^{\bullet}}{kz}\left(1 - 15\frac{z}{L}\right)^{-1/2} \ , \tag{3}$$

$$\frac{\partial v}{\partial z} = \frac{u*}{kz}\left(1 - 15\frac{z}{L}\right)^{-1/4} \ , \tag{4}$$

(Hansen, 1980; Businger, 1973; Hoffert, 1979)

where the integrated forms of equations (2) through (4) are

$$\theta = \theta_r + \frac{\theta^{\bullet}}{k}\left\{\ln\left(\frac{y - 1}{y + 1}\right)\right\}\Big|_{y_r}^{y} \ , \tag{5}$$

$$q = q_r + \frac{q^{\bullet}}{k}\left\{\ln\left(\frac{y' - 1}{y' + 1}\right)\right\}\Big|_{y_r'}^{y'} \ , \tag{6}$$

$$v = \frac{u*}{k}\left\{\ln\left(\frac{x - 1}{x + 1}\right) + 2\tan^{-1}x\right\}\Big|_{x_o}^{x} \ , \tag{7}$$

$$y = \left(1 - 15\frac{z}{L}\right)^{1/2} \ , \tag{8}$$

6

$$y' = \left(1 - 15\frac{z}{L}\right)^{1/2} \ , \tag{9}$$

$$x = \left(1 - 15\frac{z}{L}\right)^{1/4} \ , \tag{10}$$

$$x_o = \left(1 - 15\frac{z_o}{L}\right)^{1/4} \tag{11}$$

$$z_o = \text{roughness length} \ ,$$

$$L = \frac{u*^2 T_{vr}}{kg\theta_v^*} = \text{Obukhov length} \ . \tag{12}$$

(Lumley and Panofsky (1964); Van Boxel et al., 1989)

$\theta^*$ — temperature scaling length.

$q^*$ — specific humidity scaling length.

$u^*$ — friction velocity.

$T_{vr}$ — $T_r (1 + 0.61q_r)$.

$T_r$ — temperature at the reference height.

$q_r$ — specific humidity at the reference height.

$g$ — acceleration due to gravity.

$$\theta_v^* = \theta^* + 0.61\theta^*q \ . \tag{13}$$

Furthermore, since these expressions are based on the notion that the atmosphere is in steady state and horizontally homogeneous, then for unstable conditions appropriate time averages are on the order of 20 to 30 min (Hansen, 1991[*]). This is an important requirement; that is, we are working with average values.

7

Andreas (1988) expressed $\frac{dn}{dz}$ in terms of potential temperature and "absolute" humidity scaling lengths $\theta^*$ and $Q^*$. Tunick and Rachele (1991) prefer $\frac{dn}{dz}$ in terms of potential temperature and "specific" humidity to be consistent with Tatarski (1961). For example at a wavelength of 0.55 $\mu$m (Tunick and Rachele, 1991)

$$\frac{dn}{dz} = -7.9 \times 10^{-5}\frac{P}{T^2}\frac{\partial \theta}{\partial z} + \left(1.97 \times 10^{-5}\frac{P}{T}\frac{\partial q}{\partial z}\right) \, , \qquad (14)$$

where

   P = pressure in millibars,

   T = temperature in degrees kelvin.

There are several ways of determining $\theta^*$ and $q^*$ for equation (12) when $\frac{\partial \theta}{\partial z}$ and $\frac{\partial q}{\partial z}$ are expressed in similarity form using equations (2) and (3). Conceptually, the simplest approach is to evaluate equations (5) through (7) using wind, temperature, and relative humidity data measured at two heights using sensitive, but conventional sensors (Rachele and Tunick, 1991). However, experience has shown (Hansen, 1991*) that measurements from only two heights generally are not sufficient due to natural variability of the parameters and due to sensor errors. Furthermore, a disadvantage of this approach is that the measurement, logging, and processing of these data are not operationally trivial. Even so, this method was used to establish distributions of H and L'E for this study. Therefore, to clarify, the windspeed variations that are input are normally distributed with a constant value used for their variance. The H and L'E inputs, although seemingly normal with respect to their distributions (see figures 1 to 18 discussed in section 6), were modeled by the two-level method discussed immediately above. Later in section 6 we discuss the standard deviations of the derived distributions for H and L'E.

Another approach, which is theoretically more basic, makes use of turbulent fluctuation covariances and their relationship to the scaling constants, that is,

$$u^{*2} = -\overline{w'u'} \, , \qquad (14a)$$

$$u^*\theta^* = \overline{w'T'} \, , \qquad (14b)$$

$$u^*q^* = \overline{w'q'} \, , \qquad (14c)$$

*Frank V. Hansen, 1991, personal communication, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM

8

where u′, w′, and q′ are deviations (fluctuations) from their mean values. The overbar indicates an average of the fluctuation covariances.

The advantage of this approach is that it only requires measurements at one height. However, the disadvantage is that the sensors and logging equipment suitable for making these measurements are delicate and sophisticated, requiring highly skilled technicians for their operation.

Still another approach for determining the scaling contents is based on the measurement or modeling of the fluxes of sensible heat and latent heat since these fluxes are related to the scaling constants $\theta^*$ and $q^*$ as follows:

$$H = -C_p \rho u^* \theta^* \quad , \tag{15a}$$

$$L'E = -L' \rho u^* q^* \quad , \tag{15b}$$

where

   $H$    — sensible heat flux,

   $L'E$  — latent heat flux,

   $L'$   — heat of vaporization,

   $\rho$  — density of air.

The friction velocity $u^*$ in equation (15) can be approximated using the similarity relations given by equations (4), (7), and (12).

The modeling method for estimating H and L′E is based on the energy balance equations as follows. The amount of solar energy reaching the ground is modeled considering the position of the sun relative to the site of interest; the amount of energy scattered, absorbed, and transmitted by atmospheric gases and water vapor; and the longwave transmission toward the ground. Next, one considers energy reflected by the ground surface (albedo); the longwave emission from the surface; the energy absorbed by the ground, which, in turn, is either stored in the ground, used to evaporate moisture (resulting in latent heat); and finally energy that heats the air (sensible heat). The advantage of this approach is that it is heavily model oriented; the disadvantage is that it is very complex physically. In any event, the purpose of this report is not to explore the energy balance approach per se. Our question at this point is the sensitivity of H, L′E, and V in estimating $C_n^2$. Or, put a different way, how well must we estimate H, L′E, and V in our model to provide "acceptable" values of $C_n^2$. The question of whether we can do this well enough, using the energy balance approach, will be addressed in a separate study.

In this study, then, we write $C_n^2$ in terms of windspeed, sensible heat flux, and latent heat flux, assuming that their values are measured or modeled. We then consider the effect on $C_n^2$ if estimates of H, L'E, and V are assumed to be in error or vary for whatever reason. Furthermore, we assume that the variations are approximately normally distributed as found in a separate study (Rachele and Tunick, 1991) using the first method, that is, the two-level method discussed earlier.

## 2. PRIMARY EQUATIONS

We write $C_n^2$ ($\lambda = 0.55$ $\mu$m) for damp unstable conditions (Tunick and Rachele, 1991) as

$$C_n^2 = A'\theta^{*2} + B'\theta^* q^* + C'q^{*2} \, ,\tag{16}$$

where

$$A' = b\,(6.241 \times 10^{-9})\frac{P^2}{T^4}k^{-2/3}z^{-2/3}\left(1 - \gamma\frac{z}{L}\right)^{-1}\{\,\} \, ,\tag{17}$$

$$B' = b\,[3.11 \times 10^{-9}]\,\frac{P^2}{T^3}k^{-2/3}z^{-2/3}\left(1 - \gamma\frac{z}{L}\right)^{-1}\{\,\} \, ,\tag{18}$$

$$C' = b\,(3.88 \times 10^{-10})\frac{P^2}{T^2}k^{-2/3}z^{-2/3}\left(1 - \gamma\frac{z}{L}\right)^{-1}\{\,\} \, ,\tag{19}$$

and where

$$\{\,\} = \left\{\frac{\left(1 - \gamma\frac{z}{L}\right)^{1/2}}{\left[\left(1 - \beta\frac{z}{L}\right)^{-1/4} - \frac{z}{L}\right]^{1/3}}\right\} \, ,$$

b — constant — 3.2,

k — von Karman's constant (0.4),

z — height.

10

$\theta^*$ — scaling constant for temperature,

$q^*$ — scaling constant for specific humidity,

We determine $\theta^*$ and $q^*$ in terms of sensible and latent heat fluxes from equation (15); that is,

$$\theta^* = -\frac{H \times 10^3}{C_p \rho u^*} \quad , \tag{20}$$

$$q^* = -\frac{(L'E) \times 10^3}{L' \rho u^*} \quad , \tag{21}$$

where

$H$ — sensible heat flux (W m$^{-2}$),

$(L'E)$ — latent heat flux (W m$^{-2}$),

$C_p$ — gas constant — $1 \times 10^7$ (c.g.s. units),

$\rho$ — density of moist air — $10^{-3}$ g cm$^{-3}$,

$u^*$ — friction velocity (cms$^{-1}$),

$L'$ — latent heat of vaporization — $2.5 \times 10^{10}$ (c.g.s. units).

Substituting equations (20) and (21) into equation (16) gives

$$C_n^2 = A'\left(\frac{H^2 \times 10^6}{C_p^2 \rho^2 u^{*2}}\right) + B'\left(\frac{H(L'E) \times 10^6}{C_p L' \rho^2 u^{*2}}\right) + C'\left(\frac{(L'E)^2 \times 10^6}{L^2 \rho^2 u^{*2}}\right) \quad . \tag{22}$$

The friction velocity, $u^*$, is a function of H and the Obukhov length L, and L is functionally related to V. Hence, $u^*$ in equation (22) can implicitly be replaced by V.

From equations (17), (18), and (19) we note that the expressions for A', B', and C' contain the Obukhov length L, which, in turn, is a function of H, (L'E), and $u^*$, that is,

$$L = -\frac{u^{*3} T_{vr} \rho_v C_p}{kg(H - 0.61 C_p T_r (L'E)/L')} \quad , \tag{23}$$

11

where

$T_r$ — reference level temperature,

$T_{vr}$ — reference level virtual temperature,

g — acceleration due to gravity,

$$\rho_v - \text{density of moist air} = \frac{P}{R_d T_v} . \qquad (24)$$

## 3. SECONDARY EQUATIONS

For unstable conditions we write a relationship between V and L as

$$V = \frac{u*}{k}\left\{ \ln\left(\frac{x-1}{x+1}\right) + 2\ tan^1 x\right\}\Big|_{x_o}^{x} , \qquad (25)$$

where

$$X_o = \left(1 - 15\frac{z}{L}\right)^{1/4} , \qquad (26a)$$

$$x_o = \left(1 - 15\frac{z_o}{L}\right)(1/4 , \qquad (26b)$$

$z_o$ — roughness length.

The differential of V in terms of $u^*$ and x is

$$dV = \frac{\partial V}{\partial u^{\bullet}}du^{\bullet} + \frac{\partial V}{\partial x}dx , \qquad (27)$$

where

$$\frac{\partial V}{\partial u*} = \frac{1}{k}\left\{\ln\left(\frac{x-1}{x+1}\right) + 2\ tan^{-1}x\right\}\Big|_{x_o}^{x} , \qquad (28a)$$

$$\frac{\partial V}{\partial x} = \frac{u*}{k}\left\{\frac{2}{(x-1)(x+1)} + \frac{2}{1+x^2}\right\} . \qquad (28b)$$

12

However, from equation (26a)

$$dx = \frac{15z}{4L^2}\left(1 - 15\frac{z}{L}\right)^{-3/4} dL \quad .$$
(29)

From equations (28) and (29) we obtain

$$dv = \frac{1}{k}\left\{\ln\left(\frac{x-1}{x+1}\right) + 2\tan^1 x\right)\Big|_{x_o}^{x} du^*$$
(30)

$$+ \frac{30zu^*}{4kL^2}\left\{\frac{1}{x^2-1} + \frac{1}{x^2+1}\right\}\left(1 - 15\frac{z}{L}\right)^{-3/4} dL \quad .$$

Equation (30) is written as

$$dv = \alpha_3 du^* + \alpha_4 dL \quad .$$
(31)

We use equation (23) to determine the differential of L, that is,

$$dL = \frac{\partial L}{\partial u^*} du^* + \frac{\partial L}{\partial \theta_v^*} d\theta_v^* \quad ,$$
(32)

where

$$\frac{\partial L}{\partial u^*} = \frac{2u^* T_{vx}}{kg\theta_v^*} \quad ,$$
(33a)

$$\frac{\partial L}{\partial \theta_v^*} = -\frac{u^{*2} T_{xp}}{kg\theta_v^{*2}} \quad .$$
(33b)

However, since

$$\theta_v^* = \theta^* + 0.61\theta_r q* \quad ,$$
(34)

$$d\theta_v^* = d\theta^* + 0.61\theta_r dq^* \quad ,$$
(35)

and

13

$$dL = \frac{2u^*T_{vr}}{kg\theta_v^*}du^* - \frac{u^{*2}T_{vr}}{kg\theta_v^{*2}}(d\theta^* + 0.610_r dq^*) \quad . \tag{36}$$

Knowing H and L′E, and having the equations to compute u*, we can determine the differential forms of $\theta^*$ and q*, that is,

$$d\theta^* = -\frac{-dH}{C_p\rho u^*} + \frac{\theta^*du^*}{u^*} \quad , \tag{37a}$$

$$dq^* = \frac{-d(L'E)}{L'\rho u^*} - \frac{q^*du^*}{u^*} \quad . \tag{37b}$$

## 4. CALCULATION PROCEDURE

For this calculation procedure we assume that the values of H, L′E, $V_r$, $T_r$, $P_r$, and $f_r$ (reference level relative humidity) are known. We also assume that $T_r$, $P_r$, and $f_r$ are precise. The only parameters that vary are H, L′E, and $V_r$.

1. L and u* are computed interatively using equations (23) and (25).

2. Substituting $d\theta^*$ and dq* of equation (37) into equation (36) gives dL in terms of du*. Solving equations (36) and (31) gives random variations in u* and L for random errors in H and (L′E).

3. Variations in $C_n^2$ are computed using equation (22) for errors in H, L′E, and u*.

## 5. DATA SETS

The two cases considered in this study are based on field data collected at Davis, California, during the summer of 1966 (Stenmark and Drury, 1970). The Davis field site, a flat, 5-hectare area at 17 m elevation above sea level is located about 2 km west of the main portion of the University of California at the Davis Campus, 24 km west of Sacramento, and 113 km northeast of San Francisco. The data were taken during periods when the surrounding fields, for the most part, were crop covered and well irrigated, giving, in effect, homogeneous surface conditions with respect to temperature and moisture. Advection effects were considered to be negligible. Profiles of wind, temperature, and specific humidity (moisture) were measured at nine levels from 25 to 600 cm. Raw data were processed to give 1/2-h average profiles. Table 1 gives the reference level (1 m) values for windspeed $(V_r)$, pressure, $(P_r)$, relative humidity $(f_r)$, and temperature $(T_r)$, as well as the derived values for the sensible heat flux (H) and latent heat flux (L′E), for each of these cases.

14

TABLE 1. MICROMETEOROLOGICAL DATA FROM DAVIS, CALIFORNIA

|  | Case 1 | Case 2 |
|---|---|---|
| Date | 6-22-66 | 6-3-66 |
| Time (PST) | 1430 | 1200 |
| $V_r$ (cm/s) | 447.9 | 207.7 |
| $P_r$ (mbar) | 1000 | 1000 |
| $f_r$ (%) | 37.6 | 35.6 |
| $T_r$ (K) | 294.35 | 294.58 |
| H (W/m$^2$) | 66.57 | 37.92 |
| L'E (W/m$^2$) | 515.43 | 307.73 |

## 6. RESULTS

We alert the reader to a possible pitfall of misinterpretation and application of the data presented in this report. The so-called natural variations used in this study were not determined from field data; instead they are creations on our part of what we felt were reasonable. In particular we not only required that the distributions of the fluctuations be normally distributed, but we also specified the values of the variances. (Note however that the mean values were determined from field data--see section 5.) For example, the standard deviation for the windspeed distributions was 3.33 cm/s. For this study we did not try to adjust the windspeed variance to changes in the magnitude of the windspeed itself. For temperature we chose a standard deviation about the mean of 1/3 of 0.1 K. For relative humidity the standard deviation used to generate its normal distribution was 1/2 of 1 percent relative humidity. The standard deviation used for the pressure distribution was 1/3 of 1 mbar.

As far as the variances for the derived distributions for H and L'E are concerned, they (not unexpectedly) varied from case to case. For L'E the standard deviations changed from 8.0 to 11.3 W/m$^2$, for cases 1 and 2, respectively. Similarly, the change in standard deviations for H was approximately 8.1 to 6.0 W/m$^2$.

The results of two cases are presented in this section and as such are at best representations of the sensitivity of $C_n^2$ to the input parameters, as specified, and should not be interpreted as real world solutions.

Figure 1* shows the two-level model, derived distributions of H, L'E, and U* for Case 1. Additionally, the normal distributions for $V_r$ are presented to show the fidelity of the normal distributions generated and used as input parameters.

Note that the range of the distribution of sensible and latent heat for this case is approximately 50 W/m$^2$. The distribution for U* shows a narrow range and relative insensitivity to variations in the input parameters used.

---

*Figures are presented at the end of the text.

Figure 2 shows the derived distributions for $T^*$ ($\theta^*$), $q^*$, and L. The range for these distributions is approximately a factor of 2. Note that for this case, since $U^*$ is relatively large and $T^*$ is small, the mean value for the Obukhov scaling length is quite large, representing weakly unstable atmospheric conditions.

Figure 3 illustrates the random distribution for $C_n^2$ resulting from variations in H, L'E, and $V_r$. The range for the random distribution of $C_n^2$ is approximately a factor of 3. Additionally a cumulative distribution for $C_n^2$ is shown. It suggests that about 47 percent of the time $C_n^2$ will have a value equal to or less than its mean value.

Figures 4 through 6 show the distributions of H, L'E, $V_r$, $U^*$, $T^*$, $q^*$, L, and $C_n^2$ for Case 2. Note here that mean values for $T^*$ and $q^*$ are slightly greater in magnitude than those from Case 1, and the mean value for $U^*$ is small. This results in L values lower in magnitude for this case, representing more moderately unstable atmospheric conditions. $C_n^2$ is significantly larger in magnitude (that is, on the order of $10^{-13}$) and its range is approximately a factor of 5.

## 7. SUMMARY AND CONCLUSIONS

In this study we wrote $C_n^2$ in terms of windspeed, sensible heat flux, and latent heat flux. Recall that our goal was to consider the effect on $C_n^2$ if estimates of $V_r$, H, and L'E were assumed to be in error or contained natural variabilities. We used micrometeorological data from Davis, California, to evaluate distributions for H, L'E, and finally $C_n^2$. These figures were discussed in section 6.

We found that by constraining the variations for windspeed to a $\sigma$ = 3.33 cm/s and with a range of approximately 50 W/m$^2$ for both sensible and latent heat that for these two cases, $C_n^2$ could be determined within a factor of 3 or 5.

Now the question remains as to what are acceptable ranges or values for $C_n^2$. The answer lies wholly with their use, or, that is, it depends on the application for $C_n^2$. In a separate study (Rachele and Tunick, 1991), we found that $r_o$, the receiver coherence diameter, can vary (in one case) from 1.26 to 3.76 cm, causing, in turn, a significant effect upon the near- and far-field slow modulation transfer function. Other cases resulted in similar findings.

In conclusion we feel confident that our methodology was sound and that our results have the potential to suggest how well we must estimate H and L'E in our models.
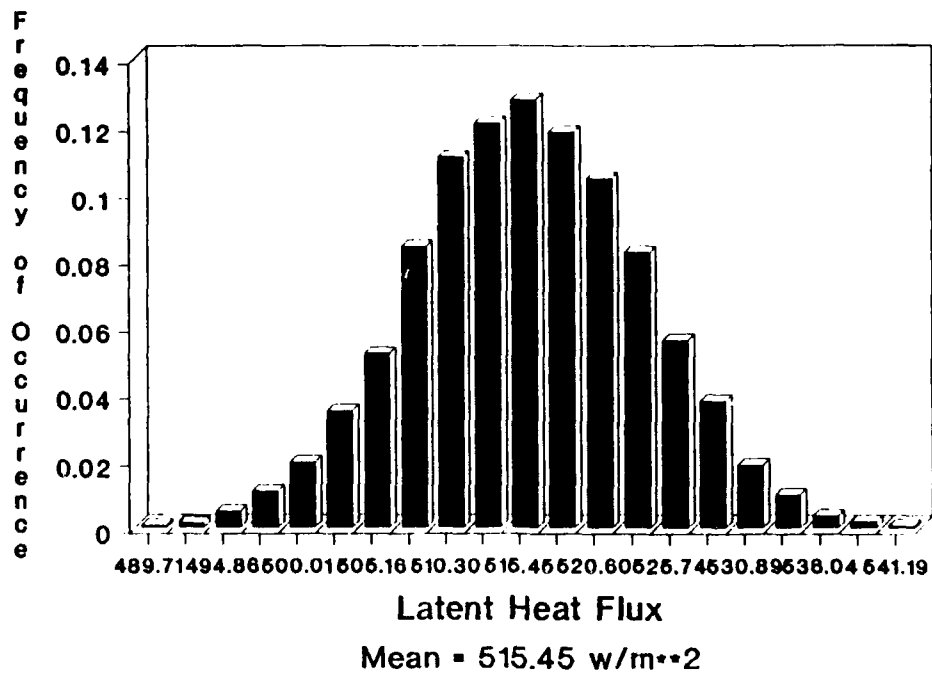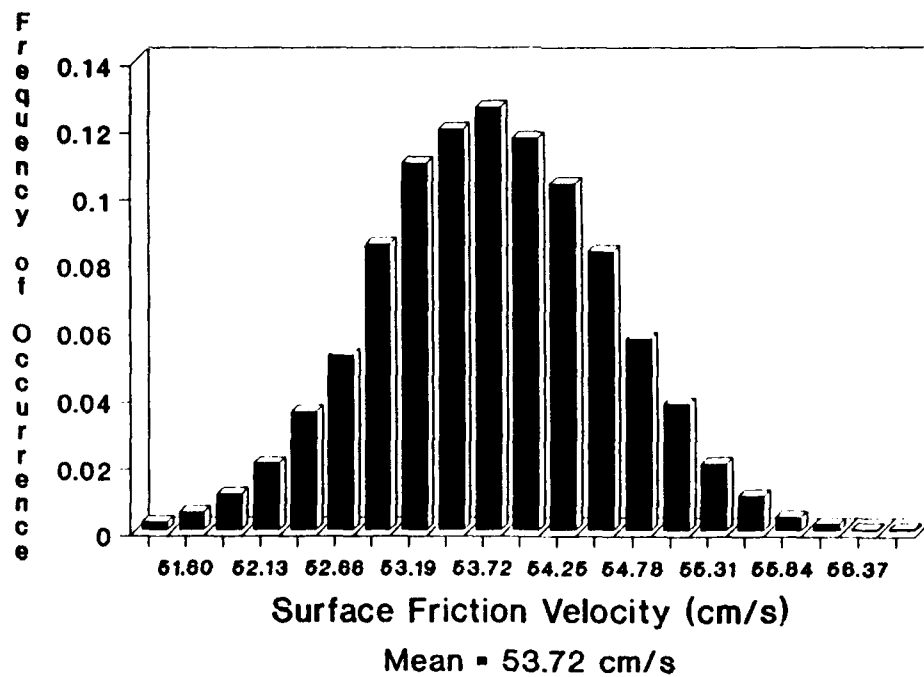
16

Mean ▪ 66.58 w/m▪▪2

(a)



Mean ▪ 447.9 cm/s
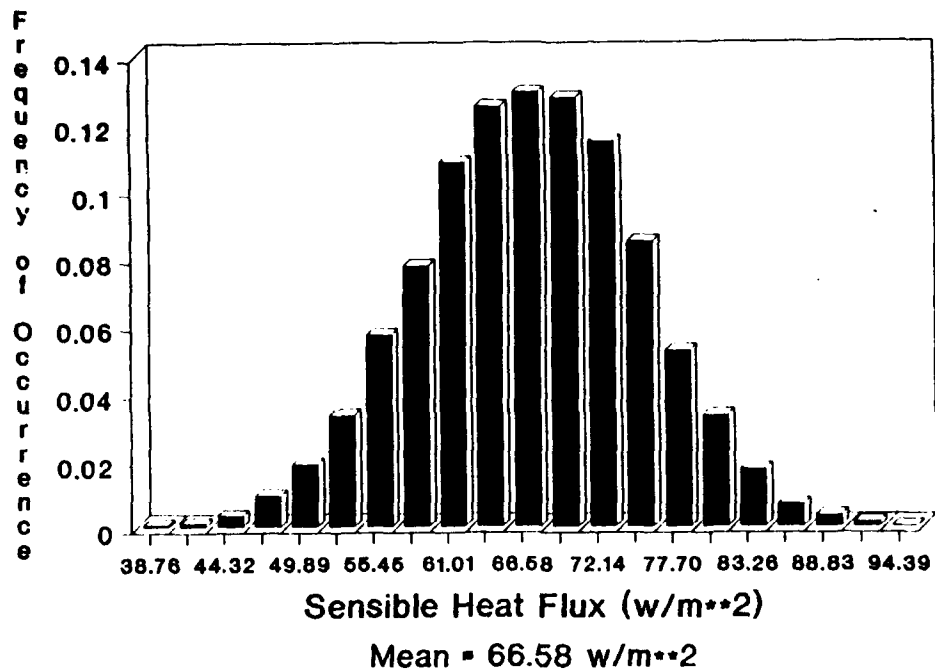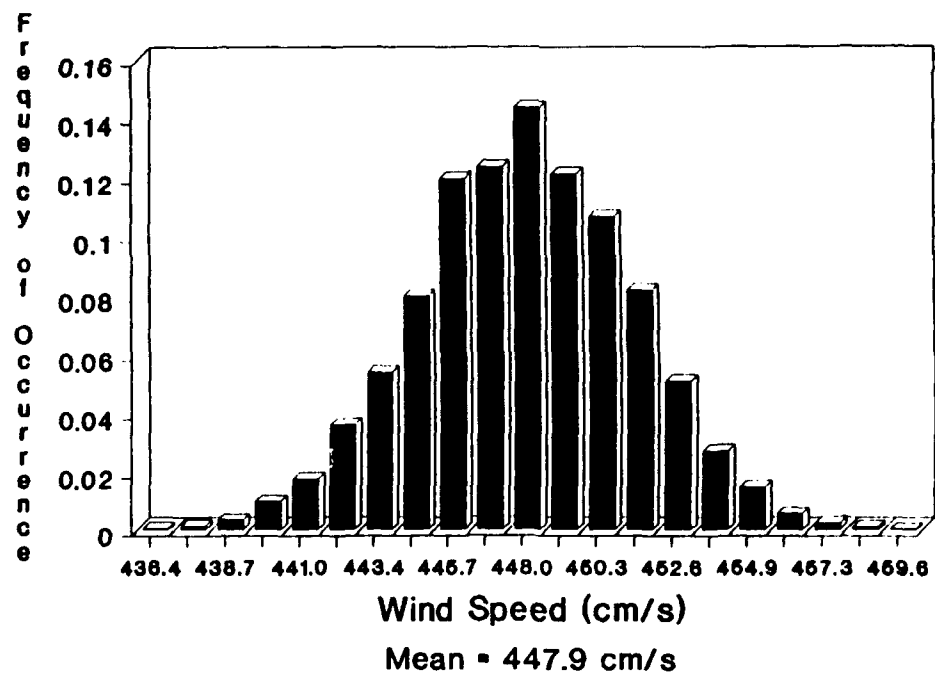
(b)

Figure 1.  Case 1 - Random distribution for:  (a) H,  (b) L'E,  (c) u*,  and
           (d) normal distribution for $V_r$.

17

Latent Heat Flux

Mean = 515.45 w/m**2
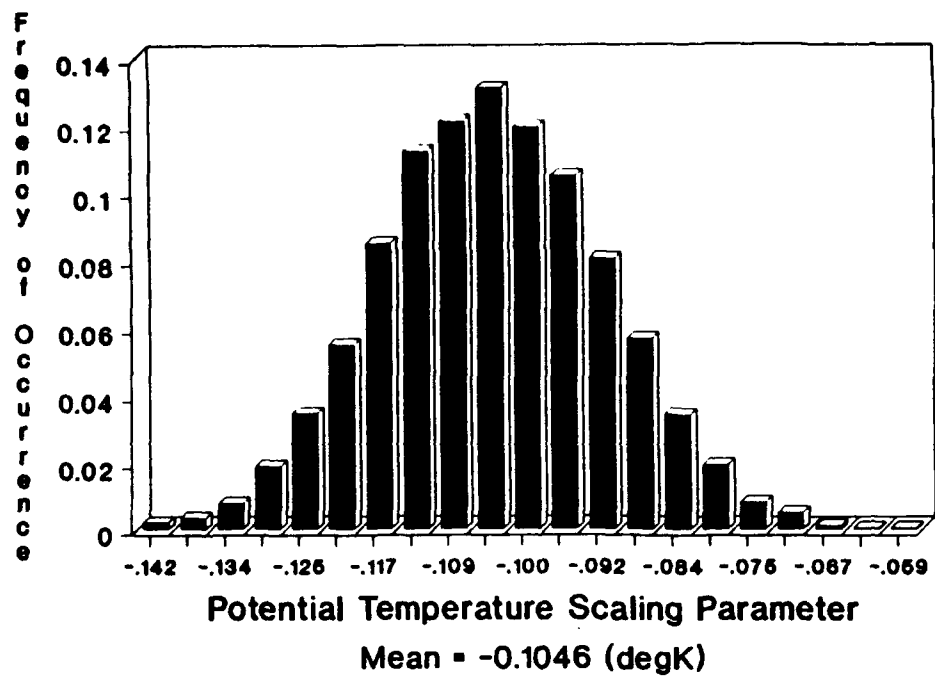
(c)



Surface Friction Velocity (cm/s)

Mean = 53.72 cm/s
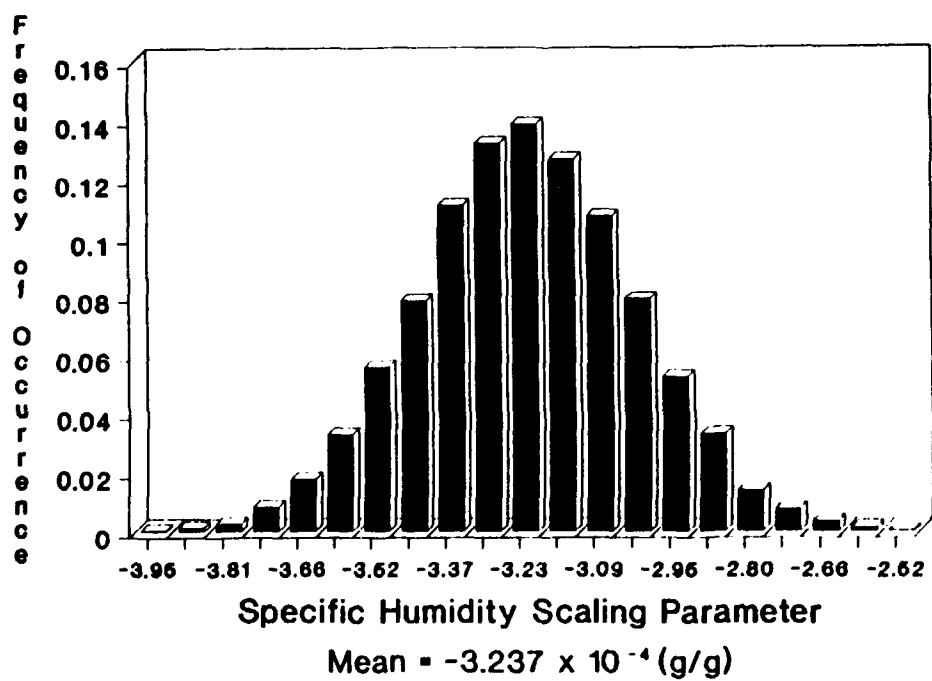
(d)

Figure 1 (cont)

(a)



(b)

Figure 2. Case 1 - Random distribution for: (a) T*, (b) q*, and (c) L.

Monin-Obukhov Scaling Length

Mean = -206.88 (m)
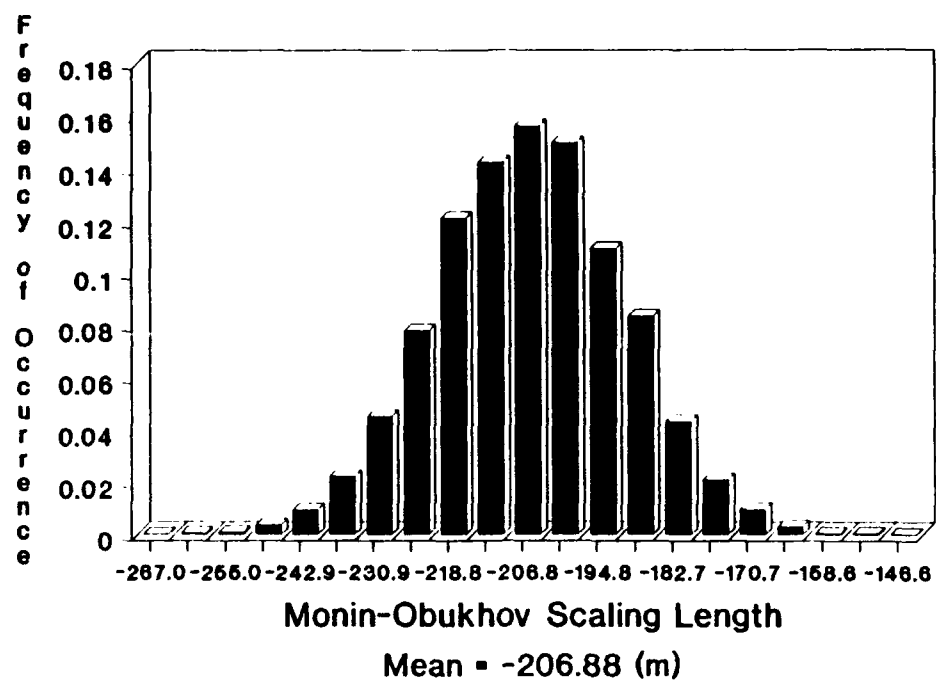
(c)

Figure 2 (cont)
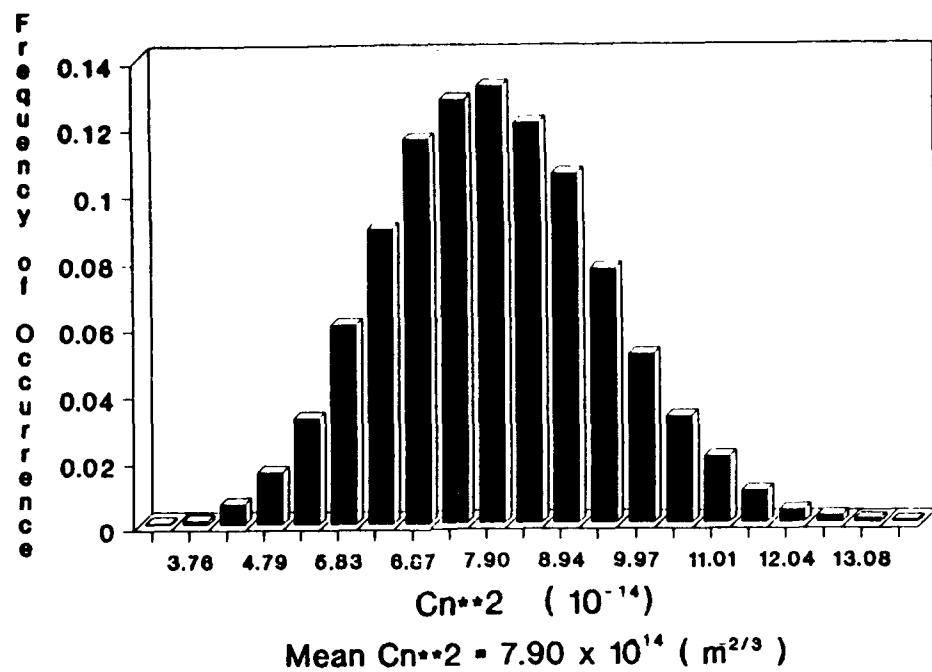
(a)



(b)

Figure 3. Case 1 - Distribution for $C_n^2$: (a) random and (b) probability.

(a)



(b)

Figure 4. Case 2 - Random distribution for: (a) H, (b) L'E, (c) u*, and (d) normal distribution for $V_r$.

Surface Friction Velocity (cm/s)

Mean = 20.98 cm/s

(c)



Wind Speed (cm/s)

Mean = 207.7 cm/s

(d)

Figure 4 (cont)

23

**Potential Temperature Scaling Parameter**

**Mean ▪ -0.1527 (degK)**

(a)



**Specific Humidity Scaling Parameter**

**Mean ▪ -4.954 x $10^{-4}$ (g/g)**

(b)

Figure 5. Case 2 - Random distribution for: (a) T*, (b) q*, and (c) L.

**Monin-Obukhov Scaling Length**

**Mean = -21.62 (m)**

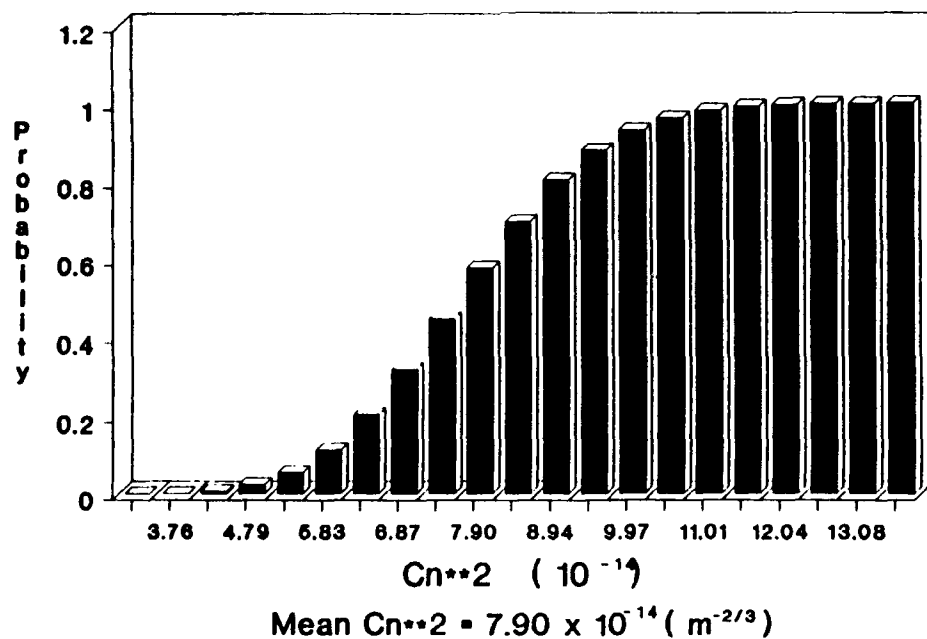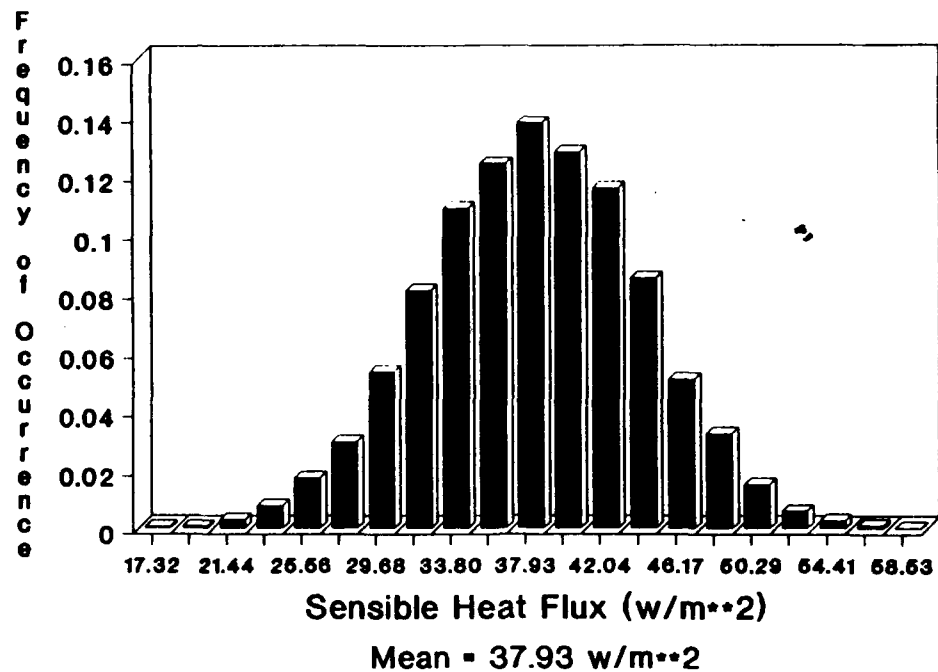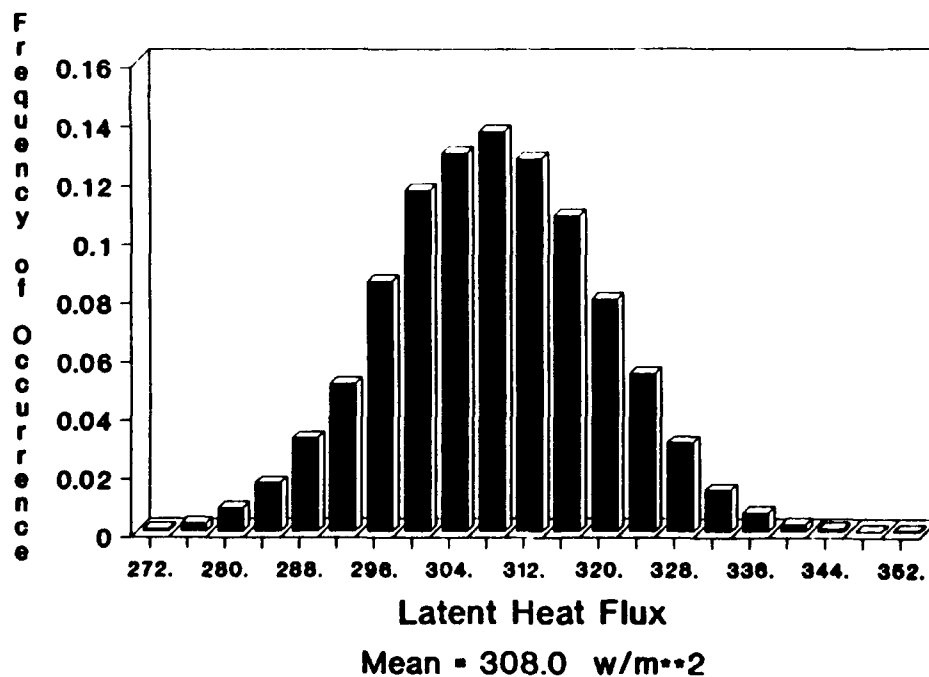(c)

Figure 5 (cont)

(a)



(b)

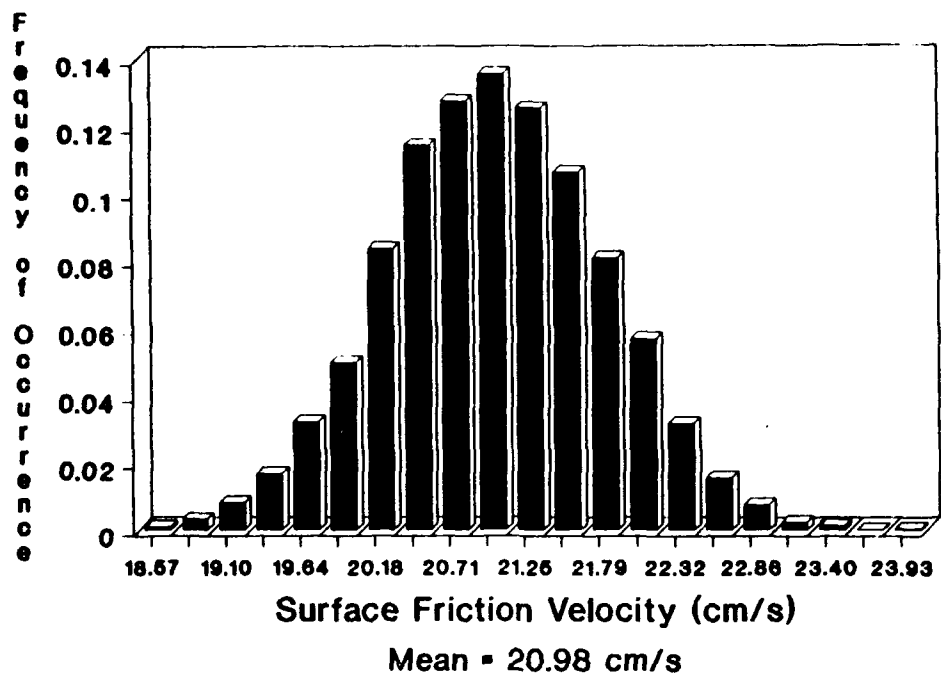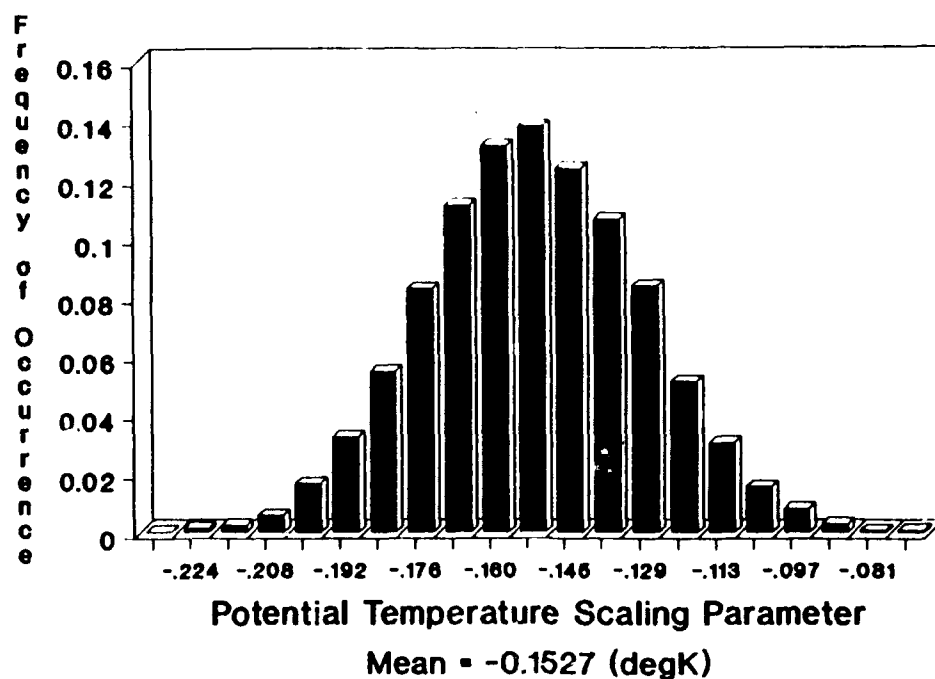Figure 6.   Case 2 - Distribution for $C_n^2$:   (a) random and (b) probability.
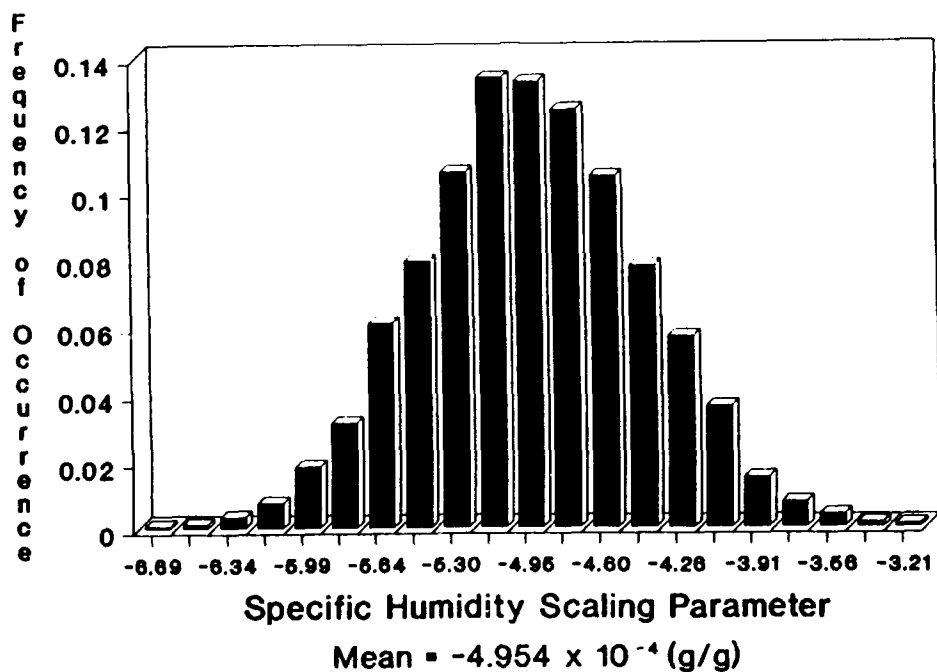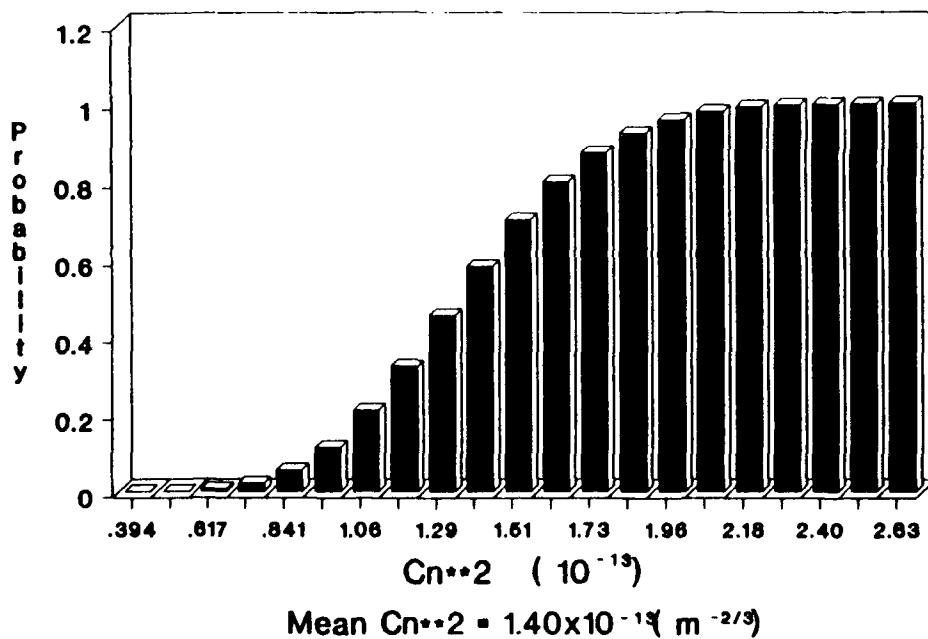
26
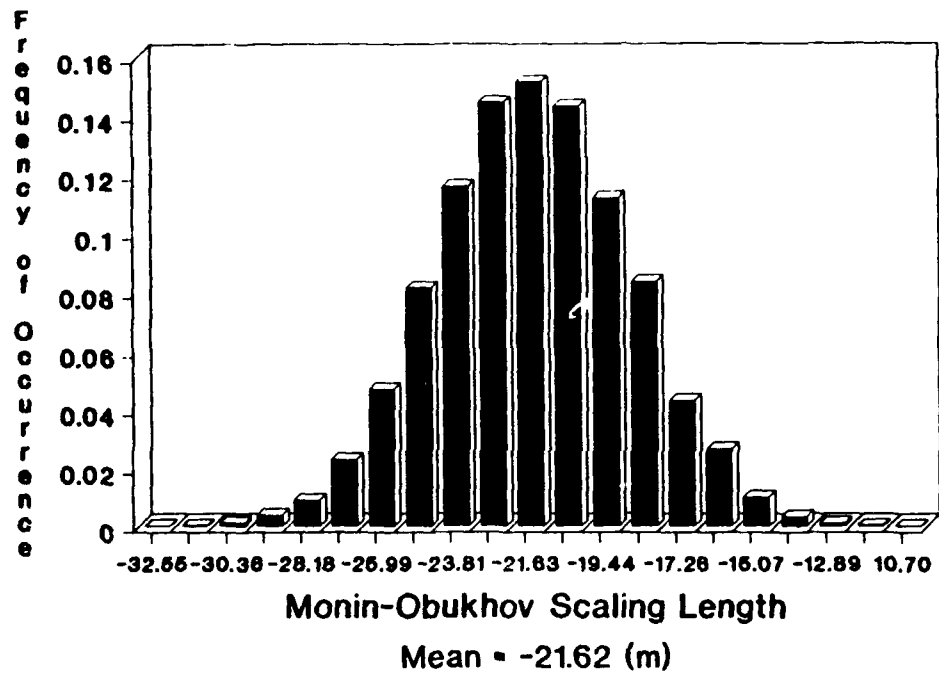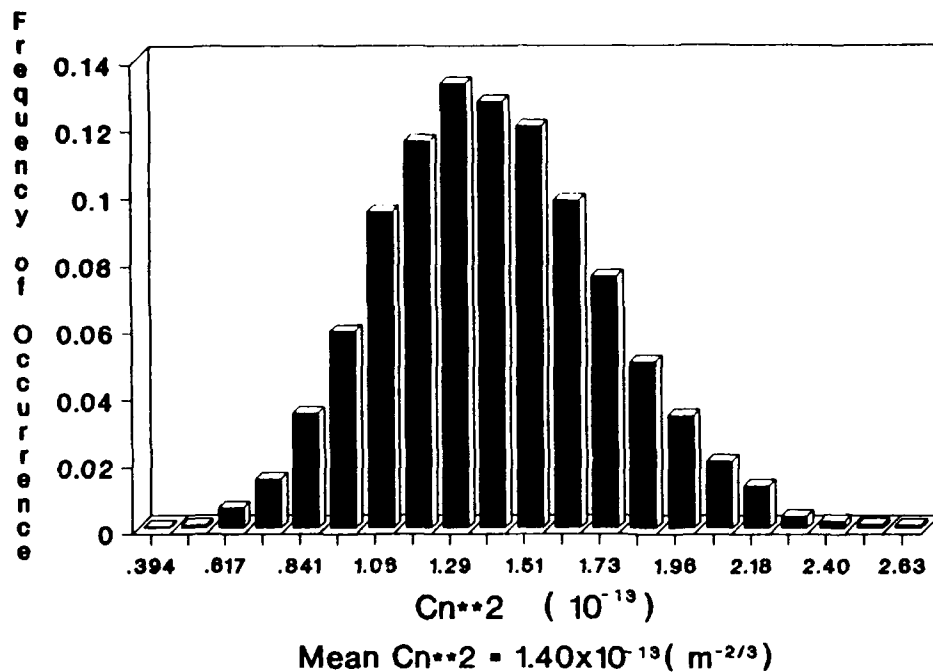
# LITERATURE CITED

Andreas, Edgar L., 1988, "Estimating $C_n^2$ over Snow and Sea Ice from Meteorological Data," J Opt Soc Am, 5:481-495.

Businger, J. A., 1973, "Turbulent Transfer in the Atmospheric Surface Layer," Chapter 2, Workshop on Micrometeorology, D. A. Haugen, editor, American Meteorological Society, Boston, MA.

Fritschen, L. J, and P. R. Nixon, 1965, "Microclimate Before and After Irrigation," Presented at the Section on Applications of Ground-Level Climatology, Annual Meetings of American Association for Advancement of Science, Berkley, California, 27-30 December 1965, Contribution from the Soil and Water Conservation Research Division, AgriZal Research Service, U.S. Department of Agriculture, Phoenix, AZ.

Hansen, F., 1980, Flux Profile Relationships for Development of Standards of Comparison, ASL Internal Report, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM.

Hill, R. J., 1989, "Implications of Monin-Obukhov Similarity Theory for Scalar Quantities," J Atmos Sci, 46:2236-2244.

Hoffert, M., and J. Storch, 1979, "A Scheme for Computing Surface Fluxes from Mean Flow Observations," Boundary Layer Meteorology, 17:429-442.

Lumley, J. L., and H. A. Panofsky, 1964, The Structure of Atmospheric Turbulence, J. Wiley & Sons, New York, London, Sydney.

Miller, Walter B., and J. Ricklin, 1990, EOSAEL 87, A Module for Imaging Through Optical Turbulence - IMTURB, ASL-TR-0221-27, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM.

Panofsky, H. A., 1968, "The Structure Constant for the Index of Refraction in Relation to the Gradient of Index of Refraction in the Surface Layer," J Geophys Res, 73:6047-6049.

Rachele, Henry, and Arnold Tunick, 1991, The Sensitivity of Optical Parameters to Variations of a Damp Unstable Atmosphere, U.S. Army Atmospheric Sciences Laboratory Technical Report (in preparation), White Sands Missile Range, NM.

Stenmark, E. B., and L. D. Drury, 1970, Micrometeorological Field Data from Davis, California: 1966-67 Runs Under Non-Advective Conditions, ECOM-6051, U.S. Army Electronics Command, Atmospheric Sciences Laboratory, Fort Huachuca, AZ.

Tatarski, V. I., 1961, Wave Propagation in a Turbulent Medium, McGraw-Hill Book Co., Inc., New York-Toronto-London (translated from Russian by R. A. Silverman).

Tunick, Arnold, and Henry Rachele, 1991, "Estimating the Effects of Temperature and Moisture on $C_n^2$ in the Damp, Unstable Boundary Layer for Visible, Infrared, Radio, and MM Wavelengths," Proceedings of the 1991 Battlefield Atmospherics Conference, U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM.

Van Boxel, J. H., F. F. Vugts, and F. Cannemeijer, 1989, "Effect of the Water Vapour Gradient on the Obukhov Length and the Profile-Derived Fluxes," Zeitschrift für Meteorologie, Band 39, Heft 6.

Wyngaard, J. C., 1973, "On Surface Layer Turbulence," Workshop on Micrometeorology, D. A. Haugen, editor, American Meteorological Society, Boston, MA, pp 101-149.

# DISTRIBUTION LIST FOR PUBLIC RELEASE

Commandant
U.S. Army Chemical School
ATTN: ATZN-CM-CC (S. Barnes)
Fort McClellan, AL 36205-5020

Commander
U.S. Army Aviation Center
ATTN: ATZQ-D-MA
  Mr. Oliver N. Heath
Fort Rucker, AL 36362

Commander
U.S. Army Aviation Center
ATTN: ATZQ-D-MS (Mr. Donald Wagner)
Fort Rucker, AL 36362

NASA/Marshall Space Flight Center
Deputy Director
Space Science Laboratory
Atmospheric Sciences Division
ATTN: E501 (Dr. George H. Fichtl)
Huntsville, AL 35802

NASA/Marshall Space Flight Center
Atmospheric Sciences Division
ATTN: Code ED-41
Huntsville, AL 35812

Deputy Commander
U.S. Army Strategic Defense Command
ATTN: CSSD-SL-L
  Dr. Julius Q. Lilly
P.O. Box 1500
Huntsville, AL 35807-3801

Commander
U.S. Army Missile Command
ATTN: AMSMI-RD-AC-AD
  Donald R. Peterson
Redstone Arsenal, AL 35898-5242

Commander
U.S. Army Missile Command
ATTN: AMSMI-RD-AS-SS
  Huey F. Anderson
Redstone Arsenal, AL 35898-5253

Commander
U.S. Army Missile Command
ATTN: AMSMI-RD-AS-SS
  B. Williams
Redstone Arsenal, AL 35898-5253

Commander
U.S. Army Missile Command
ATTN: AMSMI-RD-DE-SE
  Gordon Lill, Jr.
Redstone Arsenal, AL 35898-5245

Commander
U.S. Army Missile Command
Redstone Scientific Information
  Center
ATTN: AMSMI-RD-CS-R/Documents
Redstone, Arsenal, AL 35898-5241

Commander
U.S. Army Intelligence Center
  and Fort Huachuca
ATTN: ATSI-CDC-C (Mr. Colanto)
Fort Huachuca, AZ 85613-7000

Northrup Corporation
Electronics Systems Division
ATTN: Dr. Richard D. Tooley
2301 West 120th Street, Box 5032
Hawthorne, CA 90251-5032

Commander - Code 3331
Naval Weapons Center
ATTN: Dr. Alexis Shlanta
China Lake, CA 93555

Commander
Pacific Missile Test Center
Geophysics Division
ATTN: Code 3250 (Terry E. Battalino)
Point Mugu, CA 93042-5000

Lockheed Missiles & Space Co., Inc.
Kenneth R. Hardy
Org/91-01 B/255
3251 Hanover Street
Palo Alto, CA 94304-1191

Commander
Naval Ocean Systems Center
ATTN: Code 54 (Dr. Juergen Richter)
San Diego, CA 92152-5000

Meteorologist in Charge
Kwajalein Missile Range
P.O. Box 67
APO San Francisco, CA 96555

U.S. Department of Commerce
Mountain Administration Support
  Center
Library, R-51 Technical Reports
325 S. Broadway
Boulder, CO 80303

Dr. Hans J. Liebe
NTIA/ITS S 3
325 S. Broadway
Boulder, CO 80303

NCAR Library Serials
National Center for Atmos Rsch
P.O. Box 3000
Boulder, CO 80307-3000

Bureau of Reclamation
ATTN: D: 1200
P.O. Box 25007
Denver, CO 80225

HQDA
ATTN: DAMI-POI
Washinting, D.C. 20310-1067

Mil Asst for Env Sci Ofc of
  The Undersecretary of Defense
for Rsch & Engr/R&AT/E&LS
Pentagon - Room 3D129
Washington, D.C. 20301-3080

Director
Naval Research Laboratory
ATTN: Code 4110
  Dr. Lothar H. Ruhnke
Washington, D.C. 20375-5000

HQDA
DEAN-RMD/Dr. Gomez
Washington, D.C. 20314

Director
Division of Atmospheric Science
National Science Foundation
ATTN: Dr. Eugene W. Bierly
1800 G. Street, N.W.
Washington, D.C. 20550

Commander
Space & Naval Warfare System Command
ATTN: PMW-145-1G (LT Painter)
Washington, D.C. 20362-5100

Commandant
U.S. Army Infantry
ATTN: ATSH-CD-CS-OR
  Dr. E. Dutoit
Fort Benning, GA 30905-5090

USAFETAC/DNE
Scott AFB, IL 62225

Air Weather Service
Technical Library - FL4414
Scott AFB, IL 62225-5458

HQ AWS/DOO
Scott AFB, IL 62225-5008

USAFETAC/DNE
ATTN: Mr. Charles Glauber
Scott AFB, IL 62225-5008

Commander
U.S. Army Combined Arms Combat
ATTN: ATZL-CAW (LTC A. Kyle)
Fort Leavenworth, KS 66027-5300

Commander
U.S. Army Combined Arms Combat
ATTN: ATZL-CDB-A (Mr. Annett)
Fort Leavenworth, KS 66027-5300

Commander
U.S. Army Space Institute
ATTN: ATZI-SI (Maj Koepsell)
Fort Leavenworth, KS 66027-5300

Commander
U.S. Army Space Institute
ATTN: ATZL-SI-D
Fort Leavenworth, KS 66027-7300

Commander
Phillips Lab
ATTN: PL/LYP (Mr. Chisholm)
Hanscom AFB, MA 01731-5000

Director
Atmospheric Sciences Division
Geophysics Directorate
Phillips Lab
ATTN: Dr. Robert A. McClatchey
Hanscom AFB, MA 01731-5000

Raytheon Company
Dr. Charles M. Sonnenschein
Equipment Division
528 Boston Post Road
Sudbury, MA 01776
Mail Stop 1K9

Director
U.S. Army Materiel Systems
  Analysis Activity
ATTN: AMXSY-MP (H. Cohen)
APG, MD 21005-5071

Commander
U.S. Army Chemical Rsch,
  Dev & Engr Center
ATTN: SMCCR-OPA (Ronald Pennsyle)
APG, MD 21010-5423

Commander
U.S. Army Chemical Rsch,
  Dev & Engr Center
ATTN: SMCCR-RS (Mr. Joseph Vervier)
APG, MD 21010-5423

Commander
U.S. Army Chemical Rsch,
  Dev & Engr Center
ATTN: SMCCR-MUC (Mr. A. Van De Wal)
APG, MD 21010-5423

Director
U.S. Army Materiel Systems
  Analysis Activity
ATTN: AMXSY-AT (Mr. Fred Campbell)
APG, MD 21005-5071

Director
U.S. Army Materiel Systems
  Analysis Activity
ATTN: AMXSY-CR (Robert N. Marchetti)
APG, MD 21005-5071

Director
U.S. Army Materiel Systems
  Analysis Activity
ATTN: AMXSY-CS (Mr. Brad W. Bradley)
APG, MD 21005-5071

Commander
U.S. Army Laboratory Command
ATTN: AMSLC-CG
2800 Powder Mill Road
Adelphi, MD 20783-1145

Commander
Headquarters
U.S. Army Laboratory Command
ATTN: AMSLC-CT
2800 Powder Mill Road
Adelphi, MD 20783-1145

Commander
Harry Diamond Laboratories
ATTN: SLCIS-CO
2800 Powder Mill Road
Adelphi, MD 20783-1197

Director
Harry Diamond Laboratories
ATTN: SLCHD-ST-SP
  Dr. Z.G. Sztankay
Adelphi, MD 20783-1197

Air Force Systems Command/WER
Andrews AFB, MD 20334-5000

National Security Agency
ATTN: W21 (Dr. Longbothum)
9800 Savage Road
Ft George G. Meade, MD 20755-6000

U. S. Army Space Technology
  and Research Office
ATTN: Brenda Brathwaite
5321 Riggs Road
Gaithersburg, MD 20882

OIC-NAVSWC
Technical Library (Code E-232)
Silver Springs, MD 20903-5000

The Environmental Research
  Institute of MI
ATTN: IRIA Library
P.O. Box 8618
Ann Arbor, MI 48107-8618

Commander
U.S. Army Research Office
ATTN: DRXRO-GS (Dr. W.A. Flood)
P.O. Box 12211
Research Trianagle Park, NC 27709

Dr. Jerry Davis
North Carolina State University
Department of Marine, Earth, &
  Atmospheric Sciences
P.O. Box 8208
Raleigh, NC 27650-8208

Commander
U. S. Army CECRL
ATTN: CECRL-RG (Dr. H. S. Boyne)
Hanover, NH 03755-1290

Commanding Officer
U.S. Army ARDEC
ATTN: SMCAR-IMI-I, Bldg 59
Dover, NJ 07806-5000

U.S. Army Communications-Electronics
  Command Center for EW/RSTA
ATTN: AMSEL-RD-EW-SP
Fort Monmouth, NJ 07703-5303

Commander
U.S. Army Communications-Electronics
  Command
ATTN: AMSEL-EW-D (File Copy)
Fort Monmouth, NJ 07703-5303

Headquarters
U.S. Army Communications-Electronics
  Command
ATTN: AMSEL-EW-MD
Fort Monmouth, NJ 07703-5303

Commander
U.S. Army Satellite Comm Agency
ATTN: DRCPM-SC-3
Fort Monmouth, NJ 07703-5303

Director
EW/RSTA Center
ATTN: AMSEL-EW-DR
Fort Monmouth, NJ 07703-5303

USACECOM
  Center for EW/RSTA
ATTN: AMSEL-RD-EW-SP
Fort Monmouth, NJ 07703-5303

6585th TG (AFSC)
ATTN: RX (CPT Stein)
Holloman AFB, NM 88330

Department of the Air Force
OL/A 2nd Weather Squadron (MAC)
Holloman AFB, NM 88330-5000

PL/WE
Kirtland AFB, NM 87118-6008

Director
U.S. Army TRADOC Analysis Command
ATTN: ATRC-WSS-R
White Sands Missile Range, NM 88002

Rome Laboratory
ATTN: Technical Library RL/DOVL
Griffiss AFB, NY 13441-5700

Department of the Air Force
7th Squadron
APO, NY 09403

AWS
USAREUR/AEAWX
APO, NY 09403-5000

AF Wright Aeronautical Laboratories
Avionics Laboratory
ATTN: AFWAL/AARI (Dr. V. Chimelis)
Wright-Patterson AFB, OH 45433

Commander
U.S. Army Field Artillery School
ATTN: ATSF-F-FD (Mr. Gullion)
Fort Sill, OK 73503-5600

Commandant
U.S. Army Field Artillery School
ATTN: ATSF-TSM-TA
  Mr. Charles Taylor
Fort Sill, OK 73503-5600

Commander
Naval Air Development Center
ATTN: Al Salik (Code 5012)
Warminister, PA 18974

Commander
U.S. Army Dugway Proving Ground
ATTN: STEDP-MT-DA-M
  Mr. Paul Carlson
Dugway, UT 84022

Commander
U.S. Army Dugway Proving Ground
ATTN: STEDP-MT-DA-L
Dugway, UT 84022

Commander
U.S. Army Dugway Proving Ground
ATTN: STEDP-MT-M (Mr. Bowers)
Dugway, UT 84022-5000

Defense Technical Information Center
ATTN: DTIC-FDAC
Cameron Station
Alexandria, VA 22314

Commanding Officer
U.S. Army Foreign Science &
  Technology Center
ATTN: CM
220 7th Street, NE
Charlottesville, VA 22901-5396

Naval Surface Weapons Center
Code G63
Dahlgren, VA 22448-5000

Commander
U.S. Army OEC
ATTN: CSTE-EFS
Park Center IV
4501 Ford Ave
Alexandria, VA 22302-1458

Commander and Director
U.S. Army Corps of Engineers
Engineer Topographics Laboratory
ATTN: ETL-GS-LB
Fort Belvoir, VA 22060

TAC/DOWP
Langley AFB, VA 23665-5524

U.S. Army Topo Engineering Center
ATTN: CETEC-ZC
Fort Belvoir, VA 22060-5546

Commander
Logistics Center
ATTN: ATCL-CE
Fort Lee, VA 23801-6000

Commander
USATRADOC
ATTN: ATCD-FA
Fort Monroe, VA 23651-5170

Science and Technology
101 Research Drive
Hampton, VA 23666-1340

Commander
U.S. Army Nuclear & Cml Agency
ATTN: MONA-ZB Bldg 2073
Springfield, VA 22150-3198